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RAPID SPECTROPHOTOMETRY WITH BI-MULTIPLE SPECTRA AND A NEW TYPE OF WEDGE CELL

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ABSTRACT. A slit diaphragm for spectrographs is described by means of which the process of obtaining the absorption curves of liquids and solids is greatly facilitated. Its application to emission spectrography is considered. A new cell for absorption spectrography is also described.

1. *Introduction*

IN experiments or observations on phenomena which are dependent upon the thickness of a substance the question usually arises of what is the best way to vary, and also to measure, that thickness. Optical rotation and the absorption or diffusion of light are among these phenomena; in colorimeters, polarimeters, and spectrophotometers a number of devices have been used in which the phenomena observed are controlled by varying the thickness of liquids or solids.

Jellett* in his polarimeter varied the thickness of liquid traversed by the beam of light until the rotation of the plane of polarisation acquired a specified value. Baly and Desch†, in the well-known Baly tube used in determining the absorption of liquids, varied the thickness of the liquid in order to alter the absorption of radiation of a particular wave-length.

In order that various thicknesses may be available without adjustment, wedges of the substance have been used, as, for instance, in the well-known quartz wedge compensator of the modern saccharimeter‡, whilst Mees and

* Jellett, *Proc. Roy. Irish Acad.* 25 June 1860; *ibid.* 22 Jan. 1863. See also article "Polarimetry," *Dict. App. Phys.*

† Baly and Desch, *Trans. Chem. Soc.* **85** 1904 (1039).

‡ Soleil, *Compt. rend.* **20** 1845 (1805); **21** 1845 (426); **24** 1847 (973).

Wratten* used a wedge cell in the determination of the absorption of liquids. By means of such a cell placed in front of the slit of the spectrograph, so that at different heights the slit is illuminated through different thicknesses of liquid, they obtained wedge spectra of dyes, etc., and were thus able to obtain the absorption curves of those substances. It should be mentioned that they obtained spectra of somewhat similar appearance when, in order to determine the colour sensitiveness of photographic plates and the effect of dyes thereon, they used wedges of neutral tinted glass placed in front of the slit of the spectrograph. Such work as that just mentioned illustrates the high qualitative value of wedge spectra in absorption work, and with care the method can be made to yield useful quantitative results.

The main purpose of the multiple-aperture slit diaphragm which is described in this paper is to use the advantages of the wedge cell (an improved form of which is described) to obtain with two exposures, without any adjustment of the cell, an effect that in general requires a dozen or more exposures. The slit diaphragm and the use with it of the wedge cell in the manner to be described were suggested by one of the authors (L. J. S.), who, in the course of his frequent use of various types of ultra-violet photometer, and, in particular, in assisting various investigators in the examination of blood serum, had been impressed with the desirability of saving time by avoiding long exposures.

The importance of this economy of time, where the substance is one which changes with time or with irradiation, has recently been emphasised by Davis and Sheard†. They say "Many solutions undergo rapid chemical or physical changes on standing or on exposure to certain agencies such as heat and radiation. Clearly the absorption curves obtained for such a solution cannot be correct unless the time required for obtaining the data is less than that required for the occurrence of noticeable changes in the transmissive properties. Undoubtedly great scientific value would attach to any method which would enable us to obtain correct absorption curves for such solutions. Such a method would make it possible to follow the chemical or physical changes by means of the corresponding changes in the absorption spectra. Observations of this nature would be extremely useful in the study of biological fluids."

These authors then point out that the method of employing a quartz spectrograph and a rotating sector photometer is unable to cope with rapid changes such as they are interested in, and they proceed to suggest various modifications of the apparatus which will permit of the study of this type of phenomena. Unfortunately, the modifications suggested would lead to considerable increase in the complexity and amount of apparatus required.

In such cases, where existing methods are being forced to their utmost extent in an attempt to get further observations, it is generally advisable to attempt to open up some new line of attack upon the problem. The devices and technique described in the present paper are the fruits of such an attack, and it will be found

* Mees and Wratten, *Brit. Journ. Phot.* 1907 (384). Earlier uses of wedge cells are also described in Kayser's *Handbuch der Spectroscopie* **3** (58).

† Davis and Sheard, *J.O.S.A.* **21** 1931 (47).

that it is possible to equal and even surpass the desired speed by means of a very simple technique involving an extremely small number of operations.

2. *The Multiple-aperture Diaphragm*

The multiple-aperture slit diaphragm consists, as shown in Fig. 1, of two rows of rectangular apertures R_1, R_2; each aperture is 0·4 mm. wide, and the apertures of either row are separated from their neighbours in that row by spaces of width 0·6 mm. The two rows of apertures are staggered with respect to one another by a distance of 0·4 mm. The diaphragm is used close to the slit of a spectrograph. Since there are 15 apertures in each row, the effect of taking a photograph first with R_1 over the slit, and then with R_2 in the same position, is to produce 15 pairs of spectra, the pairs being separated by gaps of 0·2 mm. (see Fig. 4, and the curve of Fig. 5 drawn from it). Below R_2 is a larger aperture through which, when a

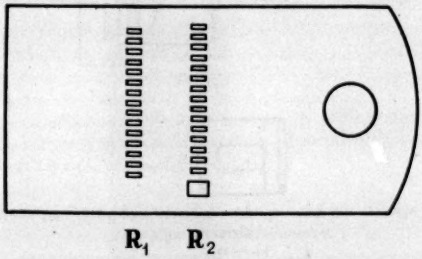

Fig. 1.

wedge cell is being employed, a trace can be obtained of the extreme bottom of the wedge cell. Hence it is possible to deduce from the photograph what is the thickness of liquid in the cell corresponding with the junction of each pair of spectra. The sizes, number, and separation of the apertures can of course be modified to suit any particular kind of work, but the above have been found very convenient for absorption spectrophotometry.

It should be noticed that, on account of the chromatic aberration of the instrument, especially when a quartz spectrograph is being employed, the vertical dimensions on the photographic plate are only the same as those of corresponding points on the diaphragm for one single wave-length. However, since the distance between consecutive apertures is exactly 1 mm., it follows that for every spectrum line on the photographic plate the interval between the common edge of one pair of spectra and that of the next pair corresponds to 1 mm. when applied to considerations of height in the wedge cell.

3. *An Improved Form of Wedge Cell*

A line drawing of the cell as it is in use is shown in Fig. 2, whilst the dimensions given in Fig. 3 are those of an actual cell used by us. The cell is made from two

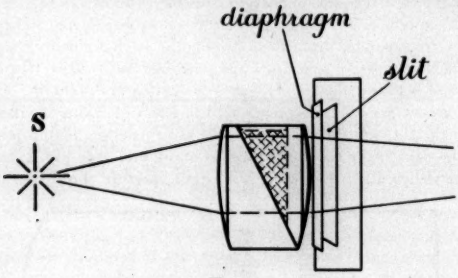

Fig. 2.

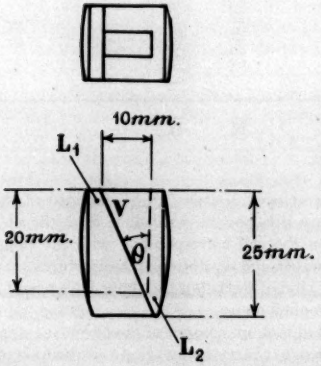

Fig. 3.

pieces of fused silica, the parts of which are made to adhere by the Hilger method (British Patent 103,233 and U.S.A. Patent 1,206,177) subsequent to the opposing surfaces having been placed in optical contact*. The cell in its final form is thus an integral whole secured in one piece without the use of any cement whatsoever. The interior of the cell is a wedge-shaped recess formed from two pieces in the

* Twyman, *Proc. Opt. Conv.* 1905 (50).

following manner. The piece L_2 has a groove ground through it, the bottom of the groove being then polished; the portion L_1 is a solid block with one flat inclined surface. On adhesion, the sloping side of the groove in the wedge-shaped piece L_2 is closed by this flat inclined surface of L_1, and a wedge-shaped recess V is thus formed.

The outer face of L_1 is lens-shaped, and collimates the light from the source S; the beam of parallel light so produced passes through the liquid under examination in the recess V, and then (the outer face of L_2 being also lens-shaped) an image of the light source S is formed on the aperture of the spectrograph prism. By this means the slit is uniformly illuminated from top to bottom by all parts of the source*.

Incidentally it may be noted that the centre of the lens system formed by the curved surfaces of L_1 and L_2 is half way between the top of the cell and the point where the thickness of liquid becomes zero; the vertical height of this liquid wedge is 20 mm.

When in use, the cell is supported in a mount which attaches to the slit of the spectrograph. When thus mounted, the cell covers one set of apertures, and the two necessary exposures are obtained merely by sliding the diaphragm along a few millimetres, so that the other set of apertures covers the slit.

During the manufacture of the cell a protector is cemented to the top of the cell to assist in the working of the lens surfaces. This protector can be used as a neat cap if the cell is used with volatile liquids.

4. *Use of the Multiple-aperture Diaphragm and New Wedge Cell in Absorption Spectrophotometry*

In the use of the diaphragm for measuring the absorption of a liquid two photographs are taken—one through the cell filled with the liquid and employing the R_2 set of apertures, the other through the R_1 set and through the same cell filled with a non-absorbing liquid. The first exposure is made considerably longer than the second one (both exposures being carefully timed), and the resulting plate exhibits 15 pairs of spectrograms (see Fig. 4). The spectrograms belonging to the R_1 set are identical, whereas those belonging to the R_2 set exhibit a variation amongst themselves in that they are obtained by passing the light through different thicknesses of the substance under examination.

Examination of the various pairs will show, if the relative exposures have been suitably chosen, that in certain pairs there are one or more places where the intensities of the two spectra are the same. Having identified these places, the extinction coefficient for these various wave-lengths can be obtained as follows with an approximation dependent on certain implicit assumptions to which we shall revert later.

Let t_1 and t_2 be the times of exposure through the absorbing liquid and non-absorbing liquid respectively ($t_1 > t_2$). Let I_2 be the intensity of the non-absorbed beam and I_1 that of the absorbed beam after passing through the absorbing liquid

* See *The Practice of Spectrum Analysis with Hilger Apparatus*. 5th edition, 1931, pp. 30 *et seq.*

at the point under consideration, I_2 being greater than I_1. For equal blackening we then have

$$I_2 t_2^p = I_1 t_1^p \qquad \text{.....(1),}$$

where p is Schwarzschild's constant.

But the extinction coefficient α is defined as

$$\alpha = (\log I_2/I_1) \div d \qquad \text{.....(2),}$$

where d is the length of path through the liquid (in cm.).

Hence $$\log I_2/I_1 = d\alpha \text{ or } I_2 = I_1 . 10^{d\alpha} \qquad \text{.....(3).}$$

We can now re-write equation (1) as

$$I_1 . 10^{d\alpha} t_2^p = I_1 t_1^p \qquad \text{.....(4),}$$

and hence

$$10^{d\alpha} = (t_1/t_2)^p \text{ or } d\alpha = p \log_{10} (t_1/t_2) \qquad \text{.....(5).}$$

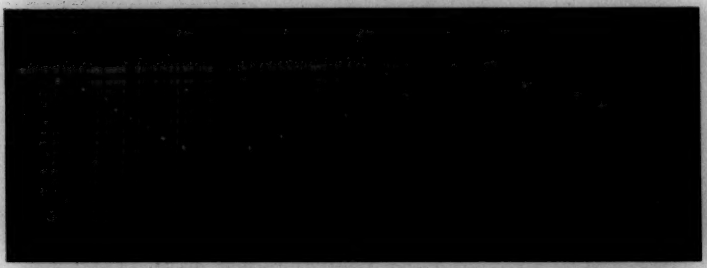

Fig. 4.

For any pair of exposures, however, d can be found from the height at which the beam of light passes through the liquid, since the angle of the wedge is known.

The purpose of the large aperture below the R_2 set will now be clear. The bottom of the wedge is photographed through this and the height of the common edge of any pair of spectra is given by $(x + n - 1)$ mm., where x is the distance of the bottom of the wedge below the junction of the first pair of spectra*, and n is the ordinal number of the pair of spectra under consideration. We thus have

$$d = \tfrac{1}{10} (x + n - 1) \tan \theta \qquad \text{.....(6),}$$

where the factor 10 enters owing to the fact that d must be expressed in cm.

With the cell shown in Fig. 3, θ (26° 34′) = $\tan^{-1} \frac{1}{2}$, whence

$$d = \tfrac{1}{20} (x + n - 1) \qquad \text{.....(7).}$$

* Measured on the plate, not in mm. of course, but in terms of the mm. as they appear on the plate—i.e. the distances between the middle of adjacent spectrum pairs for each wave-length.

Returning to equation (5), we see that it reduces to

$$\alpha = \frac{2op}{x+n-1} \log_{10}(t_1/t_2) \qquad \ldots\ldots(8).$$

The process of evaluating the extinction coefficient α is thus quite simple and straightforward: t_1 and t_2 are known, x is measured direct, n is obtained by inspection, and p, the Schwarzschild constant, may be taken as approximately unity. The point (or points) for each pair of spectra where there is the same intensity is determined by visual inspection, and reference to the wave-length scale on the plate will give the wave-lengths of these points. α is then calculated for these points

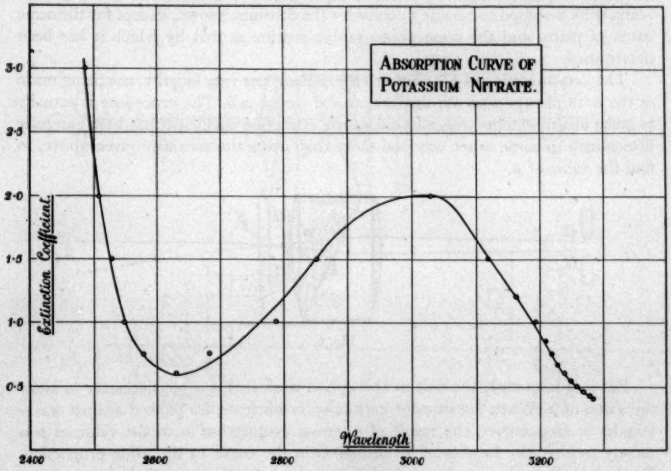

Fig. 5.

in the manner indicated above, and a curve can then be drawn with α plotted against wave-length (Fig. 5).

But we must now examine the various assumptions which are implied in the above calculation.

(*a*) It is assumed that the line of separation between each pair of spectra corresponds with a definite height of the wedge of liquid, and hence with a definite thickness of liquid.

Actually, however, this is not the case. From Fig. 6 we see that a particular point of the diaphragm receives and utilises radiation coming from all parts of the light source between the extreme rays *abcd* and *a'b'c'd*, and this radiation passes through thicknesses of liquid varying from *bc* to *b'c'*.

(*b*) It is also assumed that there is no material difference between the refractive indices of the liquid and of the cell. Actually the thickness of liquid through which the radiation passes will depend on the refractive index of the liquid, and will vary with the wave-length even with one and the same liquid.

(*c*) It is assumed that the Schwarzschild constant is unity. Actually, the value of p is a matter of some doubt. In the paper in which Schwarzschild* formulated the law of blackening in which his constant p appears, he points out that Schellen found the law of reciprocity to be exactly fulfilled for the same make of plate for which Schwarzschild found the value $p = 0{\cdot}86$. Numerous values of the constant have since been determined†. From the most cautious view, therefore, it could scarcely be assumed to be safe to consider the constant known, except for the same batch of plates and the same photographic routine as that by which it has been determined.

The determination of p is neither very difficult nor very lengthy, use being made of the multiple-aperture slit diaphragm and wedge cell. The procedure is actually to make measurements with a liquid whose extinction coefficient has been carefully determined in some other way and from this, using the formulae given above, to find the value of p.

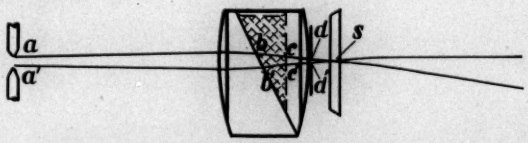

Fig. 6.

But it is frequently the case in absorption work that it is not necessary to know the value of p. When densities or extinction coefficients are plotted against wave-lengths or frequencies, the result of a wrong assumption as to the value of p is merely to alter the heights of all ordinates in the curve in the same proportion. Further, if all results are obtained with the same kind of plate and the same photographic routine, with the additional precaution of taking a check curve of a standard liquid for each new batch of plates, the results obtained will be relatively correct and, in particular, the actual positions of the absorption peaks in the spectrum will be correctly given.

If this view is taken, the observer may assume that p is unity and his curves will be of utility, provided he always bears in mind that the scale of the ordinates may be somewhat too great or too small. However, it cannot be pretended that to leave the matter in this position is entirely satisfactory, and we have therefore sought an arrangement in which these complications would not arise.

* Schwarzschild, *Astrophys. Journ.* **11** 1900 (92–9).

† Lux (*Z. f. Belichtungswesen*, **13** 1917 (83)) has found variations with wave-length of this constant up to 6·3 in the case of panchromatic plates, but these unusual values have not, so far, been confirmed.

The result is the cell shown in Fig. 7 A. It is similar in construction to that previously described, except that the outer surfaces are flat, and that on the vertical interior surface *A* are apertures which in effect are like those described in the multiple-aperture diaphragm. These apertures are produced in the following way.

Before the adhesion of the cell is effected, platinum is cathode-deposited to a density of not less than 3 on the surface *A*, upon which is fixed a crenellated protector shown in Fig. 7 B. Thus platinum is deposited as shown in Fig. 7 C over the entire surface *A*, except where stopped by the protector. When adhesion takes place this process at the same time "burns in" the platinum, which is thenceforth impervious to damage. A film of platinum so produced has been found by

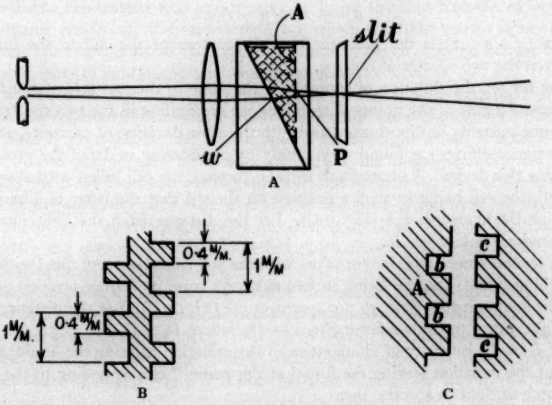

Fig. 7.

experiment to be opaque throughout the entire visible and ultra-violet spectrum as far as 1850 A.

The cell thus prepared can now be used exactly as the combination of cell and diaphragm previously described, a separate condensing lens or lenses being used to secure correct conditions of illumination. Preferably, however, instead of giving a short exposure to balance the effect of the absorption of the liquid (a process which is responsible for the introduction of the doubtful Schwarzschild constant), the light source is moved to an increased distance, either actually or in effect by means of a suitable arrangement of quartz lenses. In this form of cell the difficulties noted under (*a*), (*b*), and (*c*) above do not arise. As for (*a*) and (*b*), the range of varied thicknesses of liquid through which the radiation is received is very restricted. If we assume the length of light source (say a spark between meta

electrodes) to be 3 mm., and its *reduced* distance from the condenser 110 mm., the maximum range of thicknesses is

$$W \tan\theta \quad \text{or} \quad 0{\cdot}09 \text{ mm.}$$

$$\left(\text{since } W = \frac{3}{110} \times \frac{1}{1{\cdot}5} \times 10\right)$$

and this becomes proportionately less with decreasing thickness.

It is obvious, therefore, that in the use of the cell for photographic photometry no perceptible error will be occasioned owing to P being illuminated through liquid of various thicknesses; in short, the thickness d (in cm.) of liquid traversed will be to an accuracy well within 1 per cent. that given by equation (6), i.e.

$$d = \tfrac{1}{10}(x + n - 1)\tan\theta,$$

where $(x + n - 1)$ is the distance from the bottom of the cell to the junction between the two spectra of order n.

As for (*c*), the duration of exposure is the same in the two sets of spectra; at the wave-lengths of the points of matching we are dealing in the two spectra with the same intensity of illumination and with the same duration of exposure, and the extinction coefficient is found very simply by considering in detail the procedure of using this device. A photograph is taken through the cell (filled with absorbing liquid), the cell being in such a position on the slit that the latter is illuminated through the apertures b, b (Fig. 7 C). Let the distance from the light source to the condensing lens be D_1.

A second photograph is now taken with the cell rinsed out and filled with non-absorbing liquid; the cell being shifted sideways from its former position so that the slit is illuminated through the apertures c, c (Fig. 7 C). Let the distance from the light source to the condensing lens be D_2, where $D_2 > D_1$.

If I_2 be the intensity of illumination of the radiation entering the liquid, and I_1 that of the radiation leaving the liquid at the point P corresponding to the point of match of the two spectra, then

$$I_2 (D_1/D_2)^2 = I_1 \qquad \text{.....(9),}$$

or, since the extinction coefficient α is defined as $\alpha = (\log I_2/I_1)/d$ [where d, the length of path in cm., is, as we have seen, $\frac{1}{10}(x + n - 1)\tan\theta$],

$$\alpha = 20 \log (D_2/D_1)/(x + n - 1)\tan\theta \qquad \text{.....(10).}$$

If the Hilger variable-intensity lens system be used, the correct condition of illumination is secured. If the distance of the light source be altered a condensing lens must be used to form an image of the light source on the prism of the spectrograph.

It is the latter arrangement which we have considered to be in operation in arriving at the expression given, in which the relative intensities are derived from the distances D_1 and D_2.

The following are the considerations leading to the expression given for I_1. Assuming the light source to be correctly focussed (a condition which with a non-

chromatised condenser can only be true for one wave-length at a time), the flux of light from the source through unit area perpendicular to its path decreases as the inverse square of the distance of that area from the light source. This decrease continues up to the condensing lens, after which the light flux increases as the inverse square of the distance (reduced) of the area from the *image* of the light source. Now we are concerned with the flux of light through the diaphragm, since the optical path thereafter is such that all light passing through the diaphragm and the slit is eventually concentrated in the spectrum line on the photographic plate. Under the conditions stated the increase of flux is the same for both exposures, and can be neglected, since we are only concerned with the ratio of the flux in the case of the two exposures. D_1 and D_2 are to be measured from the light source to the condensing lens and it must be borne in mind that the expression only obtains rigidly for the wave-length for which the light source is correctly focussed. The corrections for chromatic aberration of the condensing lens are easily calculable, but are omitted here for reasons of space.

It will be seen that, by means of the apparatus and routine described, all the information required for drawing a curve connecting wave-lengths and extinction coefficients is provided by the one composite photograph, which is obtained by means of two photographs taken without shifting the photographic plate. Any necessity for more than one photograph will only arise if—at any of the match-points of the spectrum pairs—the exposure is too great or too little; in that case other photographs may with advantage be taken in which such a defect is remedied, for under- and over-exposure are alike in being unfavourable to the sensitiveness of photographic photometry.

The absorption of liquids may also be determined by the method given in Section 6, a cell with parallel ends being used instead of the wedge cell.

Another possible way of using the cell is to deposit the platinum grid upon the inclined surface of the wedge and to reflect the comparison beams from the platinum bars in such a way that it does not pass through the liquid. By suitable arrangement the intensities of the beams can be adjusted to any desired ratio and thus both exposures can be made simultaneously, without the need of shifting the cell or of replacing the liquid. Corrections would need to be introduced for variation of distance from the slit and for change of reflecting power with wave-length of the platinum. For routine tests of constancy, however, such corrections might be ignored, and the method may be of practical use in that results for the absorption curve can be derived from one exposure. This way of using the cell has not yet been tried.

5. *Sensitivity of the Multiple-aperture Diaphragm Method*

If the sensitivity of the method as already described is not sufficient when it is desired to study the finer structure of absorption curves, then one of a number of methods can be employed to increase this. When what may be referred to as the old method (employing the Hilger sector photometer) is used, the amount of detail obtainable in the absorption curve is dependent upon the number of photographs

taken. Using the diaphragm, the detail can likewise be increased by repeating the exposure with a different time-ratio from that originally employed.

With the method that we have described in this paper the sensitivity is, obviously, dependent upon the number of match-points that we can obtain from one operation. This number could be increased by diminishing the size of the apertures and moving them closer together. Practically, it would be possible to effect an improvement of (probably) 20 to 30 per cent. in this manner, but the difficulties arising in the cutting of the apertures would be much increased. Another method of increasing the number of match-points would be to cut out alternate members of the 15 comparison spectra and make each of the remaining ones do double duty by placing each of them between two of the exposures through the absorbing medium. This raises difficulty in the matter of obtaining equal spacing of the match-points.

Undoubtedly the simplest manner of increasing the scope of the diaphragm is not to cut out a number of the comparison spectra but to make each of the present ones do double duty by omitting the spacing of 0·2 mm. which at present occurs between each pair of spectra. The net effect of doing this will be to provide a match-point every 0·4 mm. instead of, as before, every 1·0 mm. The sensitivity of the method is thus increased $2\frac{1}{2}$ times over that of the original manner of using the apparatus, and the operations described in the previous section for obtaining an absorption curve, when employed with the modified aperture, would give a result which could only be obtained by taking more than 40 spectrograms when employing the sector photometer.

Should the sensitivity of the apertures and cell, as given by the modified form of aperture diaphragm just described, still not be sufficient, it could be further increased by utilisation of one of the methods described in the first two paragraphs of this section.

6. *Method of using the Devices for the Study of Absorption in Solids*

Solid material in the form of a wedge can be studied in precisely the same manner as that which we have described for liquid wedges. Often, however, solid material for investigation is in the shape of parallel-sided slabs, which may vary in thickness from a fraction of a millimetre to several centimetres; in this case the following modified method may be employed, which is also applicable to liquids contained in parallel-sided cells.

The substance under examination is placed in front of one set of apertures and a photograph is taken through it, but with a rotating logarithmic sector also interposed between the source of light and the slit. The purpose of the logarithmic sector* is to produce a diminution in intensity of the light reaching the slit, the diminution being a logarithmic function of the distance along the slit from some fixed point.

A second photograph is then taken through the other set of apertures, with

* Twyman and Simeon, *Trans. Opt. Soc.* **31** 1929–30 (169); Twyman and Harvey, *ibid.* **33** 1931–32 (1).

a shorter exposure or with the light source at a greater distance, but with neither the logarithmic sector nor the absorbing material in the path of the light. Fifteen spectrograms are thus obtained which are identical, and these are our comparison standards. The other 15 spectrograms (taken as described in the previous paragraph) are not identical, since the amount of light passing through successive apertures diminishes owing to the interposition of the sector and owing to the absorption of the substance.

Hence we can, by using results obtained from direct measurement along the slit from the fixed point, determine the relation between (*a*) the intensity of the light passing through the substance and the logarithmic sector on to the slit at some point under consideration and (*b*) the original intensity of the light emitted by the source.

In precisely the same manner as before we pick out the points in the various pairs of spectra where the intensity is the same, and, if merely a qualitative absorption curve is desired, it can now be plotted.

If extinction coefficients are desired, then we must proceed to further considerations as follows. Let the intensity of the light source be I_2; then, in the case of the non-obstructed exposure, the amount of the energy incident on the plate is proportional to $I_2 t_2$, where t_2 is the time of exposure.

In the other case, where absorption has taken place and the sector has been functioning, we find that the intensity of the light emergent from the slab (ignoring for the moment the variation due to the sector) is given by equation (2)

$$d\alpha = \log_{10} I_2/I_1,$$

which reduces to the form of equation (3)

$$I_1 = I_2 . 10^{-d\alpha}.$$

But the total time of exposure in this case is t_1 (where $t_1 > t_2$) and this has been reduced by the logarithmic sector at the point L (L being the distance along the slit corresponding to the match-point) by a fraction x, this fraction being determined solely by the sector. The resultant intensity of the light is thus proportional to $t_1 x$ and hence the energy falling upon the plate is given by $I_1 t_1 x$ which may also be written as

$$I_2 . 10^{-d\alpha} t_1 x \qquad \text{.....(11).}$$

If we put the Schwarzschild constant equal to unity, then we find that

$$I_2 t_2 = I_2 t_1 x . 10^{-d\alpha} \qquad \text{.....(12)}$$

or

$$t_2/t_1 = x . 10^{-d\alpha} \qquad \text{.....(13),}$$

and hence

$$\log_{10} (t_2/t_1) = - d\alpha \log x \qquad \text{.....(14).}$$

The factor x is to be obtained from a consideration of the equation of the sector, which is $- \log \theta = 0{\cdot}3 + 2{\cdot}0\, L$. It can be shown that this factor x is given by

$$\log x = - (0{\cdot}3 + 2{\cdot}0\, L) \qquad \text{.....(15).}$$

Hence the extinction coefficient α is finally given by

$$\alpha = \frac{\log_{10}(t_2/t_1)}{d\,(0{\cdot}3 + 2{\cdot}0\,L)} \qquad \ldots\ldots(16).$$

All the quantities on the right-hand side of the equation are known and hence α is determinable. Should it be necessary to avoid the assumption that $p = 1$, then p can be eliminated in the manner previously described, i.e. by varying the distance of the source and making $t_1 = t_2$. Both d and L, it should be noted, are in cm.

An alternative method which suggests itself is one in which the sector is used in one photograph and the absorbing material in the other. This, however, is not so good as the method described, since it means that the matching takes place on different portions of the characteristic curve of the photographic plate, whereas in the method we have given in detail the matching takes place on more or less the same portion of this characteristic curve, at any rate over a range of the spectrum for which the photographic intensity of the light source does not greatly vary.

7. *Other Applications*

Finally, although we have given in detail only two methods of using the new devices, it appears to us that there should be numerous applications. One of the most promising of these should lie in their application to the quantitative spectroscopic analysis of various substances by means of the wedge sector, since in the ordinary way of using the sector one of the main difficulties lies in the accurate ascertainment of the lengths of lines, and the matching principle now proposed obviates this.

One method of application we have in mind is as follows. A problem that frequently arises in metallurgy is to ascertain quickly the amount of one or more minor ingredients in an alloy (e.g. manganese in steel). The multiple-aperture diaphragm could be applied to this problem in the following way. Two sparks S_1, S_2 are used at the same (reduced) distance from the slit; S_1 has electrodes of an alloy in which the percentage of manganese, considered as standard, is known and is about twice what is regarded as the maximum permissible content to be sought, the electrodes of S_2 contain some other known (but less) percentage within the range of interest. These light sources are mounted on a slide so that either of them can be brought into position at will, and they are connected and run in series*. The diaphragm, with its two columns of apertures, is placed in front of the slit.

Close to the diaphragm a logarithmic sector is placed in the usual way, and this is used when a photograph is taken with S_1 in position. A photograph is then taken with S_2 in position, but with the logarithmic sector removed. The process being repeated with alloys of other known percentages in place of S_2, results are obtained from which a graph can be drawn connecting the order n (and by estimation the fraction of an order) of the spectrum pair where a match is obtained for the selected line of the substance sought and the percentage of that substance present.

* Thus forming a Barratt "twin spark" arrangement, see *The Practice of Spectrum Analysis*, 5th edition, Adam Hilger, Ltd., 1931, p. 41.

This graph can then be used to determine, by a similar process, the amount of the constituent present in an unknown specimen substituted at S_2.

Where the process is one requiring to be repeated very frequently a double slit might be used with advantage; this consists of two slits R_1, R_2 (Fig. 8) at a fixed distance from each other, such that a suitable line of the ingredient sought is brought into juxtaposition with a suitable line of the main substance, one light source alone being used.

Fig. 8.

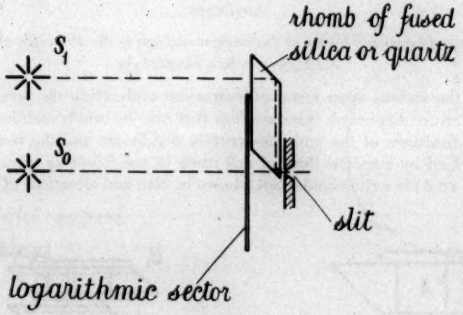

Fig. 9.

R_1 is brought into operation, with the logarithmic sector, to take a photograph of the line of the main substance, and then R_2, without the sector, to take a photograph of the line of the constituent sought.

Another possible modification is as follows. By the addition of a solid rhomb with notches in the edge (as in Fig. 11) the two photographs (through the logarithmic sector and direct) can be taken at the same time. In this way the three advantages are secured (*a*) that fluctuations in the intensity of the spectrum lines, due to fluctuations in the current, will take effect in both spectra of a pair (and thus introduce no error in comparing the spectra of each pair), (*b*) that time is saved, and (*c*) that the logarithmic sector can remain in the one position.

The arrangement intended is as follows (see Fig. 9). The two sparks S_0, S_1,

whose electrodes respectively contain the standard amount of the substance to be determined and the smaller amount required to enable the graph to be plotted, are placed at a fixed distance apart. The notched rhomb (of quartz or fused silica) receives the light from S_1 and delivers it to the slit of the spectrograph, while the light from S_0 passes through the logarithmic sector, through the notches in the edge of the rhomb, and thence to the slit of the spectrograph.

Conclusion

No purpose is to be served at this stage in recording other ways of using the multiple-aperture diaphragm; it suffices to point out that, wherever a phenomenon (such as those mentioned at the commencement of this paper) can be varied, or a variation simulated by something analogous to a wedge, one can reasonably look for a useful application of the principle of the multiple-aperture diaphragm in which by a single observation the measurement of the phenomenon can be effected for various values of its cause.

Appendix

Some Alternative Forms of Instrument employing the Principle of the Multiple-aperture Diaphragm

Among the various other forms of instrument embodying the principle of the multiple-aperture diaphragm there are four that may be briefly mentioned here:

1. The functions of the multiple-aperture diaphragm and the wedge-cell are both performed by a special form of cell made in the following way.

B_1 (Fig. 10 A) is a rhomboidal cell (shown in plan and elevation) of fused silica

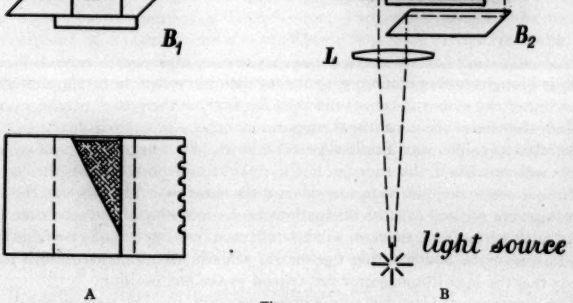

Fig. 10.

in one edge of which notches are ground. In between the two reflecting surfaces of the rhomb is the wedge-shaped recess A for the absorbing liquid. This rhomb is placed, as shown in Fig. 10 B, in front of the slit of the spectrograph in such a position that light which has traversed the cell is reflected from the projections which remain in between the notches.

A solid rhomb B_2 of fused silica (somewhat shorter than the cell) is placed in the position shown. Light from the source is received by the condensing lens L and passes through both B_1 and B_2. The light through B_2 passes through the notches of B_1 and is only allowed to pass for a fraction of the exposure; for instance,

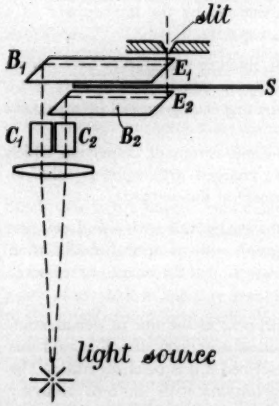

Fig. 11.

Fig. 12.

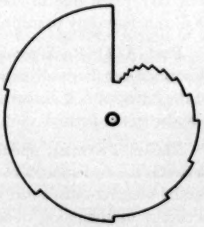

Fig. 13.

it may be interrupted by a rotating sector, or merely given a shorter time of exposure. This arrangement is equivalent to that described in Section 4.

2. Two solid rhombs B_1, B_2 (Fig. 11), of which B_1 has notches in the edge, are used as indicated, with a logarithmic sector S and two parallel-ended cells C_1 and C_2. One of the cells contains the absorbing liquid and the other a non-absorbing liquid. This arrangement is equivalent to that described in Section 6.

3. Any of the wedge cells may be built up *en échelon* in the way shown in Fig. 12; the spectrum lines taken through the liquid are thus of uniform intensity. One advantage of this is that a microphotometer may be used to determine the match-points.

4. To secure a like advantage the logarithmic sector may be stepped as shown in Fig. 13.

DISCUSSION

Dr J. S. Anderson: When Dr Houstoun and I developed a method of measuring absorption coefficients in the ultra-violet about twenty years ago*, we found that, in order to determine with accuracy the wave-length at which the two spectra to be compared had the same intensity, it was essential that the line of demarcation between the spectra should be very sharp. With the arrangement we adopted, this condition was fulfilled. It seems to me that it will not be fulfilled in the instrument the authors have described; I shall be glad to know whether this is so. Any gap or overlap could, of course, be compensated by the introduction of a suitable optical system when viewing the pairs of spectra.

Prof. L. C. Martin: I think Messrs Twyman, Spencer and Harvey have done a very useful service in making possible such greatly increased speed in ultra-violet transmission measurements, and I have no doubt that biologists will be especially grateful.

No doubt the authors have considered the slight chromatic dispersion which will take place due to the quartz prisms when charged with aqueous solution. Will this have any perceptible effect on the accuracy of the method?

Prof. A. O. Rankine: May I ask whether the wedge cell with lens faces first described can be used with the quartz spectrograph without optical modification of the latter, or is it necessary to alter the collimation so that the image of the source may be in the prism?

Messrs Twyman, Spencer and Harvey: Sharpness of the line of demarcation between the two spectra of a pair is, as Dr Anderson says, very desirable, and this can be secured satisfactorily in the apparatus described if it is carefully made. The accuracy of matching obtainable appears to correspond with the 0·02 accuracy of density determination which is usually obtainable in this kind of measurement, and this corresponds to an accuracy of 4·7 per cent. in the determination of relative intensities.

The chromatic dispersion referred to by Prof. Martin may, we find (but only in exceptional instances), necessitate a readjustment of the light source to obtain proper illumination of the shortest wave-lengths in the ultra-violet. This will be dealt with in a paper now in preparation.

In answer to Prof. Rankine's question, the wedge cell with lens faces referred to can be used with the quartz spectrograph without any modification of the latter.

* R. A. Houstoun and J. S. Anderson, *Proc. Roy. Soc. Edin.* **31** 1911 (547).

A MAGNIFICATION METHOD OF MEASURING FOCAL LENGTH

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ABSTRACT. The method described depends mainly on the determination of the distance between the two positions which the lens occupies corresponding to the reciprocal magnifications $-m$ and $-1/m$. Details of the method as applied to the measurement of the focal length of a small achromatic lens are given. The necessary precautions to be taken in making the measurements and the corrections to be applied when the curvature of field is taken into account are discussed.

Introduction

Some time ago a request was made for the measurement of the focal length of a simple achromatic lens of diameter 12 mm. when its aperture was reduced to 8 mm. The focal length was about 55 mm. and the measurement was required to an accuracy of one part in two thousand. The determination of the focal length of a lens of so small an aperture is subject to unusual difficulties which are attributable to the properties of light itself. Very unusual arrangements are called for in order to secure precise focussing, as the depth of sensibly good focus is appreciably greater than the separation of the limits corresponding to the specified accuracy. The method of measurement which was adopted enabled the uncertainty due to this cause to be reduced to a considerable extent, but not to be eliminated entirely. As there are some novel points in the method, a description of it may be of some interest.

Description of Method

The principle on which the method is based is as follows. For any pair of object and image surfaces there are, in general, two possible positions of the lens for which the magnifications are reciprocal to one another. If the distance between these positions is measured and either magnification is known, the focal length of the lens can be calculated.

In applying this principle to the lens under consideration, magnifications of -2 and $-0{\cdot}5$ were used; the distance between the object and image surfaces was thus of the order of 25 cm. Considerable care had to be taken in the choice of a suitable object and it was decided eventually to make use of a series of very fine parallel lines ruled on glass, with another line bisecting these at right angles to serve for reference purposes. Two such series were employed, one in the object space and

the other in the image space. To ensure a high degree of accuracy the glass plates were ruled by the Metrology Department of the National Physical Laboratory. Five parallel lines were ruled on each plate, the distances between adjacent lines being exactly 5 mm. For the first position of the lens, corresponding to the magnification -2, the images of the second and fourth lines on the first plate were made to coincide with the fifth and first lines on the second plate. For the second position of the lens, corresponding to the magnification $-0{\cdot}5$, the first and fifth lines on the first plate were made to coincide with the fourth and second lines on the second plate. The measurements were therefore carried out in an oblique direction and not on the optical axis of the lens. The central points of the objects and their images lay on lines passing through the centre of the lens aperture and making angles of about 3·5 degrees with the lens axis.

In order to avoid the effects of chromatic aberration, the source of illumination employed was a mercury vapour lamp, a suitable green filter being used to absorb all the prominent lines of the mercury spectrum except the one of wave-length 546·1 mμ.

The general arrangement for carrying out the experiment is shown diagrammatically in Fig. 1. The light from the source S after passing through the filter F is condensed by means of a lens C so as to illuminate the glass object plate G_1.

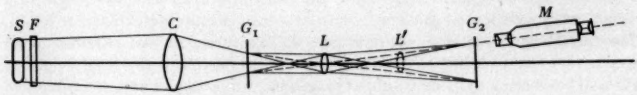

Fig. 1.

The images of the lines on G_1 are formed by the lens under test L in the plane of the image plate G_2. The coincidence of these images with the lines on G_2 is observed by means of the microscope M which can be traversed across the field of view and rotated so as to bring its axis into line with the oblique direction of observation. The second position of the lens is indicated by L', where $L'G_2 = G_1L$.

Description of Apparatus

As the displacement of the lens under test requires to be measured very accurately, it was decided to make use of a travelling microscope and to attach the lens holder to the part of the frame which normally carries the microscope.

In carrying out the experiment it is necessary that the following conditions be fulfilled:

(1) the object and image plates must be parallel to each other;

(2) the engraved lines on the image plate must be parallel to those on the object plate;

(3) the line joining the central points on the two plates (the points where the central lines are bisected by the reference lines) must be perpendicular to both plates;

(4) the optical axis of the lens must pass through the central points on the two plates.

The method of mounting the lens and the object and image plates, and the adjustments provided for enabling the above conditions to be fulfilled are illustrated in plan and elevation in Figs. 2 and 3 respectively. The optical axis of the

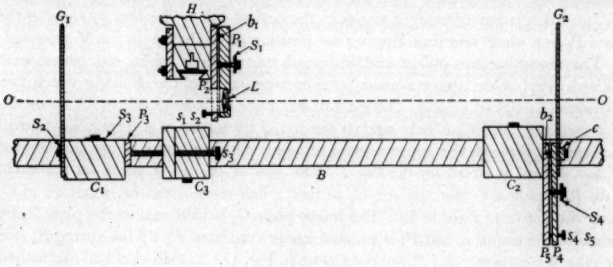

Fig. 2.

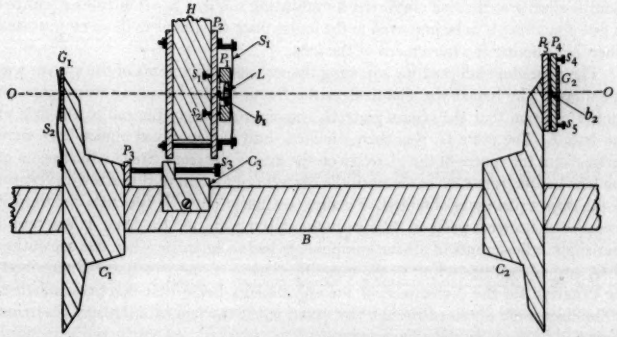

Fig. 3.

system is indicated by the broken line OO. The lens L is mounted in a recess in the plate P_1 which is pressed against the plate P_2 by means of the spring S_1. A small steel ball b_1 attached to P_2 rests in a horizontal V-groove in P_1 and two adjusting screws s_1, s_2 passing through P_2 press against P_1. The plate P_2 is bolted to the microscope holder H of the travelling microscope. This arrangement enables the following small movements of the lens to be made:

(1) a rotation about the vertical axis through b_1 by moving s_1, s_2 together in the same direction;

(2) a rotation about an axis through b_1 and the point of contact of one of the screws s_1, s_2 by moving the other screw;

(3) a rotation about a horizontal axis through b_1 by moving the plate P_1 as a whole;

(4) a displacement at right angles to the optical axis of the lens by moving the plate P_1 as a whole and thus altering the position of the ball b_1 in the V-groove.

For mounting the object and image plates, portions of an old gauge were utilised. Part of the gauge consists of a rectangular steel bar B along which two carriages C_1, C_2 can be slid. The glass object plate G_1 is held against C_1 by means of a spring S_2, and C_1 is held against the bar B by means of a spring S_3. A small carriage C_3, through the upper portion of which passes a screw s_3, can be clamped at any desired position on the bar B. The end of the screw bears on the small plate P_3 attached to the carriage C_1 so that a fine motion can be imparted to C_1 along the bar from right to left. The image plate G_2 is held against the plate P_4 by means of the clamp c, and P_4 is pressed against the plate P_5 by the spring S_4 (for the sake of clearness c and S_4 are not shown in Fig. 3). A small steel ball b_2 attached to the plate P_5 rests in a horizontal V-groove in P_4 and two adjusting screws s_4, s_5 passing through P_4 press against P_5 which is fixed to the carriage C_2. This arrangement is similar to the one employed for adjusting the lens L. It enables a number of fine adjustments to be imparted to the image plate G_2 similar to those enumerated when considering the movement of the lens.

The procedure adopted for adjusting the various components of the system was as follows. The bar B was clamped to the frame of the travelling microscope in such a position that the object plate G_1 was approximately normal to the axis of the lens L. The plate G_1 was then adjusted until the engraved object lines were vertical and the centre of the plate lay on the axis of the lens. Small adjustments of the lens holder were next made until the correct orientation of the lens with respect to the object plate was obtained. Finally, the image plate G_2 was adjusted until it occupied the correct position relative to the object plate and the lens. It was found that slight adjustments of all the components had to be made when the separation of G_1 and G_2 corresponding to the magnifications -2 and $-0{\cdot}5$ was determined, the criterion for the correctness of the adjustments being that exact coincidences of the lines were obtained for the two positions of the lens without any alteration having to be made in the adjustments.

Determination of Focal Length

The chief measurement made was that of the distance between the two positions of the lens corresponding to the magnifications -2 and $-0{\cdot}5$ for the inner and outer pairs of lines on the object plate. The mean value of six independent determinations of this distance was found to be 81·775 mm., the maximum departure from the mean being equal to one part in seven thousand. The accuracy of the final result is, of course, less than this owing to the residual uncertainty due to depth of

focus, but it is clear that the observations are as precise as the conditions are likely to allow.

The focal length of the lens cannot be obtained directly from the observations, but it may be calculated from them. The simple theory would, of course, give the focal length as being equal to two-thirds of the distance between the two positions of the lens, but, since non-axial objects have been used, a correction must be made to allow for the curvature of field. This correction may be deduced for the general case in the following way.

Let us suppose that the separation of the object lines on the plate G_1 (Fig. 4) is $2am^{-\frac{1}{2}}$ and that of the image lines on the plate G_2 is $2am^{\frac{1}{2}}$. Then, if the plates are set at right angles to the axis of the lens L and adjusted until the pairs of lines are parallel to each other and symmetrically placed with respect to the axis, the images of the object lines will coincide with the image lines for the magnification $-m$.

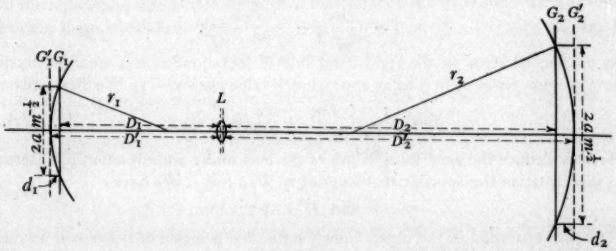

Fig. 4.

We may assume the object and image surfaces to be similar. Let their radii of curvature be r_1, r_2 respectively. Then

$$r_1 = \frac{f(1+m^{-1})}{c} \quad \text{and} \quad r_2 = \frac{f(m+1)}{c} \qquad \ldots\ldots(1),$$

so that $\frac{1}{r_1} + \frac{1}{r_2} = \frac{c}{f}$, c being a dimensionless constant (independent of m and of the focal length f) which measures the curvature of field. Now let d_1, d_2 be the distances of the plates G_1, G_2 from the positions G_1', G_2' the plates would have to occupy in order to make the axial lines conjugate with respect to the lens. Then from the properties of the circle we have

$$d_1(2r_1 - d_1) = (am^{-\frac{1}{2}})^2 \quad \text{and} \quad d_2(2r_2 - d_2) = (am^{\frac{1}{2}})^2$$

or, approximately, $\qquad 2d_1r_1 = a^2m^{-1} \quad \text{and} \quad 2d_2r_2 = a^2m.$

Substituting for r_1 and r_2 from (1), we obtain

$$d_1 = \frac{a^2c}{2f(m+1)} \quad \text{and} \quad d_2 = \frac{a^2cm}{2f(m+1)} \qquad \ldots\ldots(2).$$

Now let D_1, D_2 be the distances of the plates G_1, G_2 from the principal points of the lens and D_1', D_2' the distances of the positions G_1', G_2' from these points. Then

$$D_1 = D_1' - d_1 \quad \text{and} \quad D_2 = D_2' - d_2.$$

Inserting the values $f(1 + m^{-1})$ and $f(m + 1)$ for D_1' and D_2' respectively and substituting for d_1 and d_2 from (2), we obtain

$$D_1 = \frac{f(m+1)}{m} - \frac{a^2c}{2f(m+1)} \quad \text{and} \quad D_2 = f(m+1) - \frac{a^2cm}{2f(m+1)} \qquad \text{.....(3).}$$

If coincidence is next obtained for the second position of the lens, which corresponds to the magnification $-m^{-1}$, it is clear that from symmetry the values of D_1 and D_2 will now be interchanged. Thus the displacement of the lens, which we may denote by D, is given by the difference of these two quantities. We therefore have

$$D = D_2 \sim D_1 = \left\{\frac{f(m+1)}{m} - \frac{a^2c}{2f(m+1)}\right\}(m \sim 1) \qquad \text{.....(4).}$$

Thus

$$f = \frac{Dm}{m^2 - 1} + \frac{a^2cm}{2f(m+1)^2}.$$

As the second term on the right-hand side of the equation is a small correction term, we may replace f in it by its approximate value $Dm/(m^2 - 1)$. We therefore have

$$f = \frac{1}{m+1}\left\{\frac{Dm}{m-1} + \frac{a^2c}{2D}(m-1)\right\} \qquad \text{.....(5).}$$

We may deduce the axial focal length of the lens under consideration by inserting in this equation the appropriate values of m, D, a and c. We have

$$m = 2 \quad \text{and} \quad D = 81{\cdot}775 \text{ mm.}$$

Now the separation of the object lines for the first position of the lens is 10 mm., that is,

$$2am^{-\frac{1}{2}} = 2a/\sqrt{2} = 10$$

or

$$a^2 = 50.$$

The only unknown quantity is c. For a lens of the type under examination a reasonable value of c is 1·7 for radial focal lines and 3·7 for tangential focal lines. In deciding what value to assign to c in the present instance we must consider more closely the criterion of good focus which was adopted. As the lines engraved on the plates were extremely fine, their illumination was adjusted empirically to render them most clearly visible and a fairly high magnifying power was used in the observing microscope. In estimating the sharpness of the linear images, attention was paid to any fine irregularities that existed and it was found that the depth of focus of the fine detail was very small. We may therefore assume that the experimental observations relate to a focus between the radial and tangential focal lines, but nearer the former than the latter. On such grounds it was thought that the best value to assume for c was 2·0. Therefore

$$a^2c/2D = 0{\cdot}61$$

and equation (5) gives

$$f = \tfrac{1}{3}(163{\cdot}55 + 0{\cdot}61)$$

$$= 54{\cdot}7_2 \text{ mm.}$$

A check on the observations may be made by keeping the object and image plates fixed in position and moving the lens until the axial lines are focussed in coincidence. Then, if $-\mu$ is now the magnification, the distances of the plates from the principal points of the lens are $f(\mu+1)/\mu$ and $f(\mu+1)$ respectively. The sum of these quantities is obviously equal to the sum of D_1 and D_2 as each is equal to the distance between the plates less the distance between the principal points. We thus obtain the relation

$$\frac{f(\mu+1)^2}{\mu} = \frac{f(m+1)^2}{m} \cdot \frac{-a^2c}{2f} \qquad \text{.....(6),}$$

which we may write

$$f(m-\mu+1/m-1/\mu) = a^2c/2f$$

or

$$f(m-\mu) = \frac{m\mu}{m\mu-1} \cdot \frac{a^2c}{2f}.$$

On the right-hand side of this equation μ may be replaced by m since the difference between them is small, so that

$$f(m-\mu) = \frac{m^2}{m^2-1} \cdot \frac{a^2c}{2f}$$

or, substituting for f on the right-hand side the approximate value from equation (5),

$$f(m-\mu) = \frac{a^2cm}{2D} \qquad \text{.....(7).}$$

Similarly

$$f\left(\frac{1}{\mu} - \frac{1}{m}\right) = \frac{a^2c}{2Dm} \qquad \text{.....(8).}$$

Readings may also be taken at the centre of the field with an infinitely distant object. These settings should be distant $f\mu$ and f/μ from those taken with the axial lines focussed in coincidence. If we denote these distances by δ_1 and δ_2 respectively, we have

$$\delta_1 = f\mu = fm - a^2cm/2D \quad \text{from (7)}$$

and

$$\delta_2 = f/\mu = f/m + a^2c/2Dm \quad \text{from (8).}$$

Substituting the value of f from equation (5), we obtain

$$\delta_1 = f\mu = \frac{m}{m+1}\left(\frac{Dm}{m-1} - \frac{a^2c}{D}\right) \qquad \text{.....(9)}$$

and

$$\delta_2 = \frac{f}{\mu} = \frac{1}{m+1}\left(\frac{D}{m-1} + \frac{a^2c}{D}\right) \qquad \text{.....(10).}$$

With the lens used in the experiment a measurement of δ_1 was made and the value found was 108·171 mm. If we substitute in equation (9) the value previously obtained for D and the value 0·61 for $a^2c/2D$, we find that $\delta_1 = 108{\cdot}22$ mm., which is in very good agreement with the measured value.

Conclusions

We are justified in concluding from the results of this experiment that the method outlined is one which, if due precautions are taken and the necessary correction is made for curvature of field, will yield reasonably accurate results. It possesses the distinct advantage that errors due to depth of focus, though not entirely eliminated, are considerably reduced. A further advantage is that no knowledge is required of the positions of the principal points of the lens, all measurements being those of differences in the position of the lens. For accurate measurements it is, of course, essential that the measuring device used (in this instance the travelling microscope) should be accurately calibrated.

In conclusion I wish to thank Mr L. Buxton for his help in constructing the various adjustable parts of the apparatus.

DISCUSSION

Prof. L. C. Martin: I think it is much to be desired that somebody should go thoroughly into the subject of the measurement of "focal length," and that the present uncertain and ambiguous nature of the term should be done away with. Under the present circumstances it is hardly safe to venture on a measurement unless one knows *exactly* how the results are going to be applied. If, for example, the result of Dr Anderson's excellent and painstaking measurements were to be applied to the determination of the image size corresponding to a known angular substance for an "infinitely" distant object field, it is open to question whether the value so found would be satisfactory. In all papers such as the present, the exact relations assumed to be characteristic of the focal length have to be looked for very carefully.

In the present case the accuracy of the word depends on the effective similarity of the object and image fields (which merits a little closer discussion), and the value assumed for the constant c. In this connection it would be interesting to know whether Dr Anderson used the exact superposition of the lines or the definition of the images as the chief criterion of the setting.

I think we should be grateful for Dr Anderson for bringing the paper forward, because it illustrates very well the difficulties inherent in measurements of this nature.

Dr Anderson: I agree entirely with Prof. Martin's remarks on the desirability of having a clear definition of the term "focal length." The exact significance to be attached to the term does depend to some extent on the use to which the measurements are to be put. Unfortunately in the present instance this was not specified.

In the experiment described, considerable care was taken to obtain sharply defined images, but the exact superposition of the lines was used as the chief criterion of the setting.

NOTE ON THE ABSORPTION OF LIGHT

By R. A. HOUSTOUN, M.A., D.Sc.

(The University of Glasgow.)

[Communicated by Dr J. S. Anderson.]

MS. received, 23rd February, 1932. *Read, 10th March,* 1932.

ABSTRACT. The paper describes a verification of the law of the absorption of light in liquids and glasses over a range of intensity of 1 to 15000. The speculative views of the nature of light held at present in many quarters render it possible that the law may break down, and attention is called to the desirability of further work on the subject.

According to views held in certain quarters light consists of *photons* or units, and the generally accepted wave theory is only approximately true. There is no evidence as yet in favour of these views in the domain of ordinary optics. Indeed the position of the wave theory has been strengthened by the discovery of the crystal diffraction grating and the measurement of the angular diameter of stars since the new ideas were first promulgated. One region in which the older views might be expected to break down is that of the absorption of light. If I_0 denote the intensity of a beam at a point in an absorbing medium and I its intensity after travelling a distance x in the medium,

$$I = I_0 e^{-kx},$$

where k is a constant, the law being sometimes referred to as the Bouguer-Lambert law. It holds only for monochromatic radiation and on the assumption that no chemical change takes place, and k is supposed to be independent of the intensity I. Now this independence of the intensity might be expected to break down when I is very great, for two reasons:

(i) If absorption is explained by the elevation of electrons to a higher level in the atom, during absorption a number of electrons must be temporarily removed from the lower level. This number will increase with the intensity of the incident light. If it forms an appreciable fraction of the total number of electrons, the constancy of k will be affected.

(ii) The profile of a sound wave can be investigated by the phonograph and similar methods, but we have no means of examining the profile of a light wave. In all measurements of intensity it is averages we deal with and we know nothing of the actual intensity at any point in the train except that there must be a certain amount of fluctuation about a mean. If a limiting intensity is required to lift the electron from one level to another and this coincides with the mean about which the fluctuations take place, then the high parts of the profile will be absorbed out of the

train first, and k may depend on the proportion of the profile above a certain height.

The above reasoning is, of course, very speculative, but nevertheless it prompted me to look into the experimental proof of the law. I found that it is surprisingly slight. The fact that the index of refraction is independent of the intensity, that the velocity is constant, has been shown by Doubt* under the auspices of Michelson to one-thirtieth of a wave-length over paths up to 12 metres and an intensity range of 1 up to 290,000 for air, water, and carbon bisulphide, but the truth of the companion law for absorption rests rather on the fact that it is in use over a somewhat restricted range of intensities and has been found to work well, rather than on any specific verification. This lack of proof is commented on by H. Kayser† and by George Jaffé‡. The latter describes a verification by v. Halban and Siedentopf for a solution of potassium chromate in aqueous caustic potash according to which the molecular extinction coefficient remained constant to about one part in four thousand, when the intensity was approximately doubled.

I have consequently made a verification of the law myself. As instrument I employed a spectrophotometer of the Hüfner type which has already been described§ and as source of light a 500 c.p. "Pointolite." The diamond of the latter was focussed by a large lens on the slits of the spectrophotometer, giving an illumination there of 6000 metre-candles. This could be reduced to 60 metre-candles by inserting a plate of neutral glass in the path of the rays and to two-fifths of a metre-candle by inserting three pieces of fogged photographic plate in the path of the rays in addition to the neutral glass. Thus the intensity could be varied over a range of 1 to 15,000. Observations were made on a piece of neutral glass and solutions of blue-black ink and fuchsin.

The equation $I = I_0 e^{-kx}$ gives $kx = \log I_0/I$, whence $x\,dk = -dI/I$. Dividing this equation by the previous one,

$$\frac{dk}{k} = -\frac{dI}{I \log I_0/I}.$$

The power of the eye to detect changes of intensity, dI/I, is given us. The quantity to be measured is dk/k. It can obviously be obtained with greater accuracy when I_0/I is large. In working the spectrophotometer there are, however, objections to matching the fields too near the positions of extinction. It increases error due to stray light and the nicol is so sensitive to slight displacements in this region, that the process of setting it is somewhat difficult. I therefore arranged to have the fraction transmitted $\frac{1}{3}$ or thereabouts; this value seemed most favourable for the detection of the quantity involved.

I found the law absolutely true for the three substances in question over the whole range investigated. At first small, but definite, deviations were found at the

* Doubt, *Phys. Rev.* **18** 1904 (129).
† H. Kayser, *Handbuch der Spectroscopie*, Bd. III, § 8.
‡ G. Jaffé, *Handbuch der Experimentalphysik*, Bd. III, p. 317.
§ R. A. Houstoun, *Phil. Mag.* **15** 1908 (282).

lowest illumination. These were traced to the Purkinje effect. For example the following was a set of results obtained for the neutral glass:

6000 metre-candles	0·0868
60 metre-candles	0·0855
$\frac{3}{8}$ metre-candle	0·0779

The numbers give the fractions transmitted for green light, each being the mean of four determinations. For the purpose of these measurements the prism was removed from the spectrophotometer and a Wratten green tricolour filter substituted. At the high illumination the piece of dimming glass already referred to was held in front of the eye of the observer; at the medium illumination it was placed between the slits and the "Pointolite." Thus in both cases the field had the same brightness to the eye. To produce the low illumination the pieces of fogged photographic plate were inserted before the slits; this made the field as dark as was comfortable for accurate work. Thus at the high and medium illuminations the field had one brightness and at the low illumination it had another. There was a very slight difference in colour between the two halves of the field, the light transmitted by the glass under test being yellower than the light which came direct from the source. It is to this difference in colour combined with the difference in brightness that the change in the transmission coefficient at the low illumination is due, because, when the measurements at the medium illumination were made with the dimming glass between slits and Pointolite and the three fogged photographic plates between nicol eyepiece and eye, the transmission coefficient came out 0·0790 (mean of four determinations). Thus, when the Purkinje effect was eliminated, the difference disappeared.

Even when the light transmitted by the substance tested was resolved by the prism of the spectrophotometer, the Purkinje effect was troublesome, because at the low illumination I had to work with a fairly wide slit, and the error could be eliminated only by taking the experiment in two steps, one from the high to the medium illumination and the other from the medium to the low illumination, and keeping the intensity of the field constant during each step. In the case of fuchsin, owing to the necessity of spectral resolution, it was not possible to reach such a low illumination as in the case of the neutral glass or blue-black ink.

Thus my results were negative. No purpose would be served by giving tables of results; the figures already given may be taken as typical. I do not think the accuracy can be increased for the same great range by visual methods. The purpose of this paper is to call the attention of those who are developing photographic and electrical methods of spectrophotometry to the problem. It is possible that these methods may admit of greater accuracy, and it is desirable that the proof of the law should be placed on as firm a basis as possible. I may add that I found the "Pointolite" a very satisfactory source of light for my purpose.

NOTE ON REFRACTIVE INDICES

By Mrs E. GIFFORD

[Communicated by Mr. T. Smith.]

MS. received, 9th February, 1932. *Read*, 10*th March*, 1932.

ABSTRACT. The refractive and dispersive properties of some liquids and crystals are compared with those of glasses of similar mean dispersion.

The following table has been compiled to show how the refractive and dispersive properties of certain liquids and crystals differ from those of glasses of similar mean dispersion.

Material	$\mu_C - \mu_{A'}$	$\mu_F - \mu_C$	$\mu_{G'} - \mu_F$	$\mu_D - 1$
Cyclohexane	0·002389	0·007582	0·004501	0·429001
Glass	0·002737	0·007580	0·004173	0·499597
Nicotine	0·004644	0·015099	0·008995	0·529390
Glass	0·005049	0·015682	0·009399	0·621020
Benzene	0·005125	0·016733	0·010571	0·504551
Glass	0·005372	0·016582	0·010077	0·612974
Fused quartz	0·002523	0·006751	0·003685	0·458477
Glass	0·002516	0·006896	0·003822	0·488102
Quartz (ordinary ray)	0·002870	0·007769	0·004275	0·544256
Glass	0·002793	0·007979	0·004440	0·508325
Quartz (extraordinary ray)	0·002951	0·008040	0·004417	0·553366
Glass	0·002861	0·008042	0·004552	0·512288
Calcite (ordinary ray)	0·005534	0·013432	0·007687	0·658355
Glass	0·004299	0·013198	0·007831	0·569451

It will be seen that liquids disperse less than glass at the red end and more than glass at the violet end of the spectrum, while crystals disperse more than glass at the red end and less than glass at the violet end. Liquids have a lower refraction than glass of similar dispersion, while crystals have a higher one. Fused quartz is like the crystals in the matter of dispersion in the red and violet, but like the liquids in the matter of refraction. No glass of very nearly the same mean dispersion as nicotine could be found, so that this liquid does not show the above properties well, but it probably would if such a glass could be found. Water, sea-water, fluorite, and calcite (extraordinary ray) are of such low refraction and dispersion that they cannot be compared with any glass.

The indices used were observed by my husband, the late Colonel Gifford, and have all been published, but I do not think that the above comparison has been made before.

REVIEWS

Opticks or A Treatise of the Reflections, Refractions, Inflections and Colours of Light. (Reprinted from the Fourth Edition.) By Sir Isaac Newton. Pp. xxx + 414; 56 Figs. (London: G. Bell & Sons, Ltd., 1931.) Price 6s. net.

The work of Sir Isaac Newton has been the subject of much discussion during the last decade. The sensation caused by the verification of Einstein's predicted bending of light at the total eclipse of May 1919 drew attention to the theory of gravitation constructed by Einstein upon his general theory of relativity, and to the correction that was found necessary in Newton's law of gravitation, in order to account for the motion of the planet Mercury. The question whether Newton has, or has not, been superseded by Einstein was much to the fore ten years ago. And though serious students of science realised that in this case, as in all cases of scientific progress, there was no question of supersession but of continued development, the personal element asserted itself, nevertheless, with the result that interest in Newton's character, mode of thought, and scientific achievements was widely stimulated. It happened that a few years later, namely on March 20th, 1927, occurred the two-hundredth anniversary of Newton's death, an occasion that was celebrated by a large gathering of British scientists, who united in paying homage to the memory of Newton at his birthplace, and in the town and school where he spent his youth, and, indeed, in the very garden where his first thoughts on gravitation occurred to him.

But an even more powerful agent for stimulating interest in Newton's work has been the remarkable revolution in thought produced by the new quantum theory, based on the epoch-making experiments which have brought us the conviction that light propagation, while exhibiting many properties characteristic of waves, exhibits at the same time properties characteristic of particles; and that material particles, when sufficiently small, while exhibiting many properties characteristic of particles, exhibit at the same time properties characteristic of waves. If light is after all corpuscular in character, even if only partially, is this not a remarkable vindication of Newton's own intuitions on the subject?

It was, therefore, a happy thought that led Messrs Bell to issue a re-print of Newton's *Opticks*. This book was first published in 1704, when Newton was already over sixty years of age, and, in fact, nearly forty years after his first experiments in Optics. Although Newton probably began his experiments on the spectrum in 1666, and his first discoveries were published in the *Transactions of the Royal Society* in 1672, no full account was published till a whole generation had passed. By then, Newton had made his great discoveries in gravitation, and had developed views about the physical causes of both gravitation and light. His experiments on the colours of thin plates had led him to the famous theory of fits of easy reflexion and transmission; and although the first edition of the *Opticks* did not deal with what is nowadays called diffraction, the second edition, issued in 1717, contained Newton's remarkable speculations on this subject, with that brilliant intuition of polarisation which has meant so much to the development of the wave theory of light, both in the old elastic solid theories and in the more modern electromagnetic theory. Other editions appeared, during Newton's own lifetime in 1721, and after his death in 1730. The present reprint is from the last and fourth edition, which, we are informed, was printed from a copy of the book corrected by Newton's own hand.

We do not read scientific classics nowadays. New books are continually being written, consisting mainly of condensed reproductions of what is contained in these classics. Owing to the steady, cumulative effects of scientific progress, and the need for enabling the

student to assimilate more and more knowledge in the brief space of time that he can devote to his studies, it is necessary to foreshorten the accounts of the great discoveries of the past. Yet no more stimulating reading can be imagined for anybody interested in optical theory than this book written by Newton in that remarkably clear style of exposition characteristic of him.

Newton's mind was dominated by the principle of causality, and he was always searching for the physical picture which could exhibit in concrete form the results of his investigations. This was beautifully expressed in Professor Einstein's message to the Grantham celebrations, in which he said "May the spirit of Newton's method give us the power to restore unison between physical reality and the profoundest characteristic of Newton's teaching—strict causality." The explanations and theories in this book are a fascinating illustration of Newton's insistence on strict causality, and will be read with interest to-day in spite of the modern fashion of talking about the passing of causality.

In a brief foreword, Professor Einstein pays an eloquent tribute to Newton's unique genius, that he is so fond of acknowledging. Professor Whittaker contributes an Introduction, consisting of a delightfully lucid statement of the development of Newton's discoveries in Optics, and their relationship to wave theory and to quantum theory.

The book can be read by practically everybody who has had a reasonable secondary school education in physics. It should be particularly commended to teachers of physics, who would do well to get their pupils to repeat some of the experiments devised, carried out, and described by Newton. S. BRODETSKY.

Newton: The Man. By Lieut.-Col. R. de VILLAMIL, R.E. (Ret.). Pp. vi + 111; 1 Plate. (London: Gordon D. Knox, 1931.) Price 3*s.* 6*d.* net.

In science we do not often exhibit curiosity as to the personal fortunes and characters of the authors of great discoveries. We talk about Boyle's law, or Hooke's law, or Euler's theorem, or Laplace's equation, or Hamiltonian systems, without being very conscious of the fact that, behind each of these names, and the hundreds of others continually referred to by scientists, are to be found interesting personalities, endowed with human virtues, and limited by human vices; that these men and women lived lives of tragic and comic drama, lives characterised by fulfilment and by disappointment, lives of passion as well as of placid contentment, lives characterised by all the varying qualities that are to be found in the character of man. Newton was not merely an inventor of the calculus, a discoverer of the spectrum, and an architect of that structure of universal gravitation that goes by his name; he was also a man and a citizen; a son to a widowed mother; a brother, a nephew, and an uncle. He was a pupil and a teacher, an experimenter and a thinker, a man of science and a man of affairs. Newton was a combination of supreme scientific generosity with a rather narrow intolerance of criticism and difference of opinion.

We therefore welcome the book by Col. de Villamil. It is not a book which can be described as a life of Newton, or as dealing with any important feature of Newton's history or work. It is, as the author so aptly puts it—

> simply a small chapter in History and gives a view of Newton from a specially selected standpoint. Had it been in French, I should probably have given it the title of *Le Grand Newton en pantoufles*, since that is the view of England's great genius that I have endeavoured to adopt. This title, however, cannot be translated into English without degeneration into burlesque; the nearest I could get to it was *Newton: The Man*.

The fundamental content of the book consists of two parts. The first is "A true and perfect Inventary of all and singular the Goods, Chattels, and Credits of Sir Isaac Newton at the date of his Decease." This list is so complete and so detailed that we could easily refurnish every room in Newton's house (if it still existed) as it was at the time of his death.

This inventory is not only of the furniture, curtains, etc., of each room, but gives a list of the plates, dishes, chocolate and coffee pots, and even the cooking utensils in the kitchen—as well as the sedan chair in the stable. The second content of the book is a catalogue of the library of Dr James Musgrave, Rector of Chinnor, Oxon, this being part of the library belonging to Newton, which after his death passed into the hands of John Huggins, Warden of the Fleet Prison, and a neighbour of Newton in St Martin's-in-the-Fields. Huggins paid £300 for the library, and sent the books to his son, Charles Huggins, who was Rector of Chinnor.

Col. de Villamil is to be heartily congratulated on the discovery, both of the inventory, and of the 860 books that still remain unscattered of the original Newton library.

The book contains a very interesting contribution by Col. de Villamil himself, in which he describes the discovery of the inventory and of the library, and also, basing himself upon the evidence afforded by these, writes a number of notes about Newton's work, characteristics, and his business affairs.

The author tells us that Newton did not care for poetry, and lacked a sense of humour, being never inclined to see the funny side of things. He thinks that most modern mathematicians are equally lacking in a sense of humour, and tells us that when mathematicians "try to be funny their jokes are of an elephantine character," Lewis Carroll and P. E. B. Jourdain being exceptions!

We learn that Newton was not musical. Apparently he never played any instrument and never sang. He never drew or painted in any artistic sense. The pictures in his house were of no particular value. Newton seems to have been particularly fond of the colour red. Nearly everything in his house was crimson. The curtains were of crimson mohair. Newton's bed was furnished with crimson bed curtains and red quilts. In the dining-room there was a crimson settee. The author believes that Newton's irritability was due to the influence of this colour.

Apparently Newton had no passion for the beautiful. All the furniture in his house was neither beautiful nor valuable. There was no luxury in Newton's house. Thus, although jugs and basins were then used in bedrooms for washing purposes, this was not the case in Newton's house, where people washed in pails and tubs. Newton did not play very much even as a boy. He played cards as a student, and also some chess. In later years he played backgammon with Flamsteed. He was not fond of animals, and never had any pets. It is a little difficult to say why the author should suggest that Newton was not fond of children. His attention to his own younger relations was always most tender.

The author devotes considerable space to a discussion of Newton's transactions in connection with the South Sea Stock. He refutes the suggestion that Newton gambled, and explains Newton's activities as ordinary business transactions, and not as attempts to obtain undue profits. He even suggests that Newton's judgment was at fault in buying the stock, and tries to prove that Newton actually lost by trusting to the soundness of the South Sea Company. In order to explain the rather large sum of money left by Newton at his death, namely £30,000, Col. de Villamil shows how his salary as Warden, and later Master, of the Mint would have yielded more than enough to account for this fortune, especially as, although very generous to others, Newton spent very little on himself. He had only two suits of clothes at his death. The whole value of his cellar, most of which was bottled cider, was only £14. 16*s*. 6*d*. A French visitor who dined at Newton's house complained that the food was detestable, and that Newton was so stingy that the wine which he offered to his guests consisted of other peoples' presents to himself.

There is very much more that is interesting in the author's rambling account of *Newton: The Man*. There is also a Foreword by Professor Einstein, who refers to the author's suggestion that Newton was the inventor of the Calculus of Variations. Everybody interested in Newton should spend an hour in reading Col. de Villamil's little book.

S. Brodetsky.

Tables Annuelles de Constantes et Données Numériques. Table des Matières des Volumes I à V. Années 1910 à 1922. Rédigée par G. Kravtzoff. Pp. lxiii + 382. (Paris: Gauthier-Villars et Cie, 1930.) Price relié 400 fr., broché 370 fr.

It might be supposed that the problem of indexing the subject matter of scientific and technical literature is a matter of patience rather than of intrinsic difficulty. But this is far from the case. A really useful index of any magnitude requires patience and considerable labour to construct, it is true, but the inter-relation of scientific matter and the repercussion of one science upon another render the task of exposing the contents of the literature for ready reference so formidable that no one mind can deal adequately with the problem.

Indexes may be divided into two main classes: the alphabetic in which the terms expressing notions are arranged in alphabetical order; and the systematic in which the notions themselves, expressed it may be by lengthy phraseology, are classified and represented by an ordered system of symbols capable of combination. These two main classes are not wholly independent, for any alphabetic system cannot reach any magnitude and avoid hopeless confusion without some understructure of classification and no systematic index is complete without an alphabetical index of leading terms.

The great work before us is a striking example of these remarks. It represents the result of patience and labour, the magnitude of which only dawns upon the mind with repeated trials of its utility.

It consists of three parts—the Analytical Index, the Alphabetical Index, and the Formula Index. The first is a pseudo-classification of leading terms and has been formed by amalgamation of the analytical indexes in four languages published in each of the Volumes I to V of the Tables Annuelles. The second is a pure alphabetical index of certain terms, comprising names of animal, vegetable, and mineralogical species, biological, mineral, and industrial substances without definite formulae, common names of substances with definite formulae, followed by their empirical formulae and miscellaneous terms. This index is in French, but a number of the more important terms appear in their proper alphabetical position in the German, English, and Italian equivalents. But the greatest of the three is the Formula Index, and to use it with intelligence a set of rules set out in the Introduction must be digested. It contains all substances with definite formulae cited in the five volumes, arranged according to their empirical formulae. It is therefore a systematic index with empirical chemical formulae functioning as an ordered system of symbols, and it is completed by a part of the second or Alphabetical Index.

An examination of the Formula Index brings home to the mind the stupendous task the compilers have so ably completed. If we turn to **Cu. Cuivre** for example, we find more than four and a half columns of printed matter giving the volume and page of data concerning the physical and chemical properties not only of the pure substance but of its numerous alloys and chemical compounds, arranged in French in strictly sub-alphabetical order. Moreover the data are subdivided to the last detail by indicating special characters with smaller type in brackets. Thus, we find: **Pouv.** (oir): *émissif* 4_1, 331, 5_1, 329, *réflect.* 4_1, 334, 336 (infra roug).

To push the index to such detail greatly increases the labour of compilation and opens an additional avenue for error. The real utility of fine detail in any index is questionable for this very reason. Any conscientious searcher for data on the reflection of the infra-red from copper would hardly be content with the one reference 4_1, 336 given, but for fear of possible error would turn also to page 334 of part 1 of volume 4 and thereby rest more content in confirmation of the indexer's accuracy. On doing this, however, he will find that data on ultra-violet radiation is given, so that to be consistent...(ultraviol) should follow 334.

Of all the subjects in Science and Technology, Organic Chemistry and Pathology stand foremost as the most difficult to index. No complete international nomenclature for organic substances exists and the systems which are employed are not always the same. So that it would appear that the only systematic method of indexing organic substances is by the order of their empirical formulae as exemplified in the work under review. But this method suffers from the defect that the empirical formula has to be set up according to specified rules before the index can be consulted. Such rules are given in the Introduction as previously stated. One ventures to ask whether this troublesome and difficult problem is not more easily approached by adopting once and for all an employed classification of organic substances supplemented with as complete an alphabetical index as possible.

It is not the intention of the reviewer to enter into a discussion of this pressing question, but an example of what is suggested may be found in the *Classification Décimale Universelle**, where the system adopted by Victor Meyer and Paul Jacobson in their *Lehrbuch der Organischen Chemie* has been utilised.

Misprints are bound to occur in a work of this magnitude, but those that have been noticed are insignificant. Thus we find in the Analytical Index, p. xxix under Viscosity, Waxes and Fats, 4_1, 69 which is incorrect, but in the Alphabetical Index we find the correct reference,

Graisses. Visc. 4_1, 70.
Cire. Visc. 4_1, 70.

On the whole this work is a remarkable production and is essential to those who seek data in the rapidly increasing volumes of the Tables Annuelles.

One wonders how the compilers will deal with the problem of indexing as the years roll on and the volumes increase in numbers and parts. Is it their intention to publish quinquennial indexes and repeat the expenditure of labour and money or is it their intention to publish an accumulative index? If the latter, an example of how this serious and costly task might be approached in an economical manner will shortly be published as the first annual index to the British Power and Fuel Bulletin.

A. F. C. POLLARD.

La Lumière Monochromatique, sa Production et son Emploi en Optique Pratique (Deuxième Edition entièrement refondue). Par Ch. Fabry. Pp. 40; 16 Figs. (Paris: Revue d'Optique théorique et instrumentale, 1930.) Price 5 fr.

This brochure, first published in 1923, forms a compendious account of the means of production and the various applications and uses in physical and technical optics of monochromatic light. The book would serve as an introduction to the more practical and manipulative side of the subject suitable for students who have already gained familiarity with its broader aspects in their general studies. The employment of monochromatic light in an optical laboratory is of such frequent occurrence and so many phenomena and processes are dependent upon it that the presentation of this aspect of the subject in a special chapter such as this needs no further justification.

After a preliminary consideration of definitions the author proceeds straight to the subject of light sources, and gives a description of the various types which are of utility in practice, together with their important characteristics.

The following section takes for its subject the various applications of monochromatic light in the interferometry of thin and thick plates. Some grounding in the subject is here assumed, and the bearing in particular applications of the type and nature of the

* Published at l'Imprimerie de l'Institut International de Bibliographie, 101 rue Piers, Brussels.

illumination and the method of observation is considered in special relation to the radiation employed.

A brief mention is made of the employment of monochromatic light in tests upon the chromatic aberration of lens systems, and in a concluding section the applications to refractometry, absorption photometry, and polarimetry are briefly touched upon. Thus the plan of the book and its material execution remain substantially as in the first edition.

In the paragraphs setting forth the theoretical conditions upon which the phenomena depend the argument is clear and succinct, and in this respect the book constitutes a valuable résumé. In some other respects, however, it is less valuable, particularly in relation to more recent developments: thus, for example, we find the wave-lengths in current employment in refractometry represented as still those solely of the spectra of hydrogen and sodium, while no mention is made of the necessity in some work of obtaining a higher purity of radiation than that afforded by simple filtration or dispersion, and how such may in general be achieved. The book is also not free from printer's errors.

Such, however, are minor blemishes in comparison with the general scope and purpose of the book, which as an introduction to the subject of its title can be recommended to all students and workers in optics.

J. W. P.

Die optischen Instrumente, Brille, Lupe, Mikroskop, Fernrohr, Aufnahmelinse und ihnen verwandte Vorkehrungen. (Vierte Auflage.) Von Dr Moritz von Rohr. Pp. v + 130; 91 Figs. (Berlin: Julius Springer, 1930.) Price RM. 5.70.

This most useful little book has been brought thoroughly up to date by Prof. von Rohr. It is designed not to teach its readers how to design optical instruments, but how to use them intelligently. It is a great pity that this book has never been translated into English, as its mode of presentation and its systematic handling would have made it very valuable. It fulfils two essentials required in any intelligent treatment of optical instruments: (1) the stops which limit the ray-pencils passing through the instrument are discussed in every case, (2) the fact that an eye or a photographic plate must be placed behind the optical instrument must always be considered. Then Prof. von Rohr, as we would expect, gives valuable historical notes as he goes along. He first discusses the fundamental relations between the object and image-spaces and the entrance and exit pupils and windows of general optical systems. Then follows a chapter on the eye, at rest, in accommodation, and in motion. He then treats of optical instruments—spectacles, the magnifying glass, the microscope (magnification, ray-passage, resolving power, the objective, the ocular, the condenser), telescopes (terrestrial, astronomical, and binocular), the photographic lens, the verant and projection apparatus. Considering the size of the book, the information given is very comprehensive. For example, a considerable treatment is given of perspective, seeing with two eyes, the resolving power of the microscope, the field of the Galilean telescope, and an account is given of the aberrations of a photographic lens.

The modern type used is an advance on the not always easily legible German type used in the earlier editions.

This small book still remains a classical introduction to the study of optical instruments, and should be known to a wider circle of English readers.

N. M. S. L.